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Design of a new system of high-power efficiency conditioning cogeneration energy for a building of the University of Cagliari with fossil fuel plants.

Paolo Giuseppe Mura[a*], Roberto Innamorati[a]

[a]University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy

Abstract

An analysis of Italy's National Energy Budget of in the last decades shows the important role of the civil sector and the impact of fossil fuels in air conditioning systems. The high consumption of fossil fuel is Likely due to the predominance of plants with conventional boilers in buildings. Based on the analysis of the Exergy flow this paper proposes the Cogeneration technology for Air conditioning systems with heat pumps to implement the Rational Use of Energy. The feasibility of a retrofit intervention on existing systems of a large size is shown, by the projection of a cogeneration plant for the buildings of the University of Cagliari currently equipped with fossil fuel plants.

Keywords: Cogeneration energy; reducing climate altering CO_2;

1.Introduction

The limited results of the Kyoto Protocol in the verification of 2012 and the commitment arising from the new European energy plan summarized in the "20-20-20" lead us to identify the areas of intervention that can contribute significantly to reducing climate altering CO_2 emissions and dependence on imported energy commodities. The analysis of the evolution of the National Energy Budget of the past 15 years can help to identify areas where it is useful and can intervene with rationalization. It is known that the civil sector absorbs about 30% of the demand for energy and air conditioning systems are largely responsible; however the recent interventions made in the past have not always produced the desired effects; such as the widespread use of low-power heat pumps is perhaps detrimental to the national energy budget. Therefore it is necessary to perform an analysis based on the fundamentals of Thermodynamics and Energy to identify the technologies and methodologies that lead to an energy saving and environmentally friendly optimization of Air conditioning plants.

* Corresponding author. Tel.: +39-070-675-5269; fax: +39-070-675-5263.
E-mail address: murapg@gmail.com

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2. Energy analysis of the civil sector

In order to set on a solid experimental basis a proposed " technology system " which presents the prospect of possibly becoming part of the technology to be incentivized in the national energy policy, we present the most salient results of the analysis of the National Energy Budget of the last fifteen years , with particular attention to the data for "Civil Sector". Tables 1 and 2 presented below, taken from BEN 1998, 2010 and 2013 prepared by the National Government [1], it focuses in particular on the end-use in the three main sectors: Industry, Transport, Civil.

Table 1. Summary of data related to the National Energy Budget of Italy

	Italia 1998		Italia 2010		Italia 2013	
Areas of use	[Mtoe]	[%] of end use	[Mtoe]	[%] of end use	[Mtoe]	[%] of end use
Total gross domestic	179		188		173	
Total end use	131		138.6		126.6	
Transportation	40	30	42.4	30	38	30
Civil	39	30	49.5	35	49	39
RES Civil	1.05	3(*)	3.15	7.2(*)	6.7	13.7(*)

The table 1 shows that if the total gross domestic consumption after 2010 has decreased to the value of 1997 it is not due to the National Action Plan for the implementation of the Kyoto protocol, but a result of the severe economic and financial crisis internationally and in Italy; In fact, the decrease of about 15 Mtoe, as seen from Table 1, is due to the reduction of the energy used in industry and in the transport sector (a known link to industrial activity); whereas an effective Rational Use of Energy should not cause an economic crisis, but rather contribute to increasing the productivity of the national economy. These values of the evolution of energy demand confirm a macroeconomic law with foundations in physics, the correlation between the economic production measured by GDP and the demand for energy in the economic system [2]. It can also be seen that the end use of energy in the civil sector is always a fraction more than 30% of the total end use, in addition its value has remained at a constant of around 49 Mtoe during the more acute years of the economic crisis. Table 2 shows that in the Civil Sector the share of fossil fuels has increased from 1998 to 2010, but has held at around 30 Mtoe in recent years, despite the economic crisis; This trend is expected because homes, schools, canteens, government offices, hospitals, markets, etc. continue to perform functions that now need air-conditioning as a “minimum comfort” for users; consequently the civil sector remains dependent for more than 60% on imports with the high cost of natural gas and oil, despite decreases in the short term. Therefore, this area is also among the main causes of negative environmental conditions and climate-altering CO_2 urban emissions.

Table 2. Analysis of the data relating to the Civil Sector of the National Energy Budget of Italy

Topic	Italy 1998	Italy 2010	Italy 2013
End use [Mtoe]	39	49	49,5
Comb.Foss. Civil[Mtoe]	28,2	32,1	29
RES Civil [Mtoe]	1,05	3,15	6,7
Comb.Fos/Civil [%]	72	65	58,6
RES/Civil – [%]	2,7	6,4	13,7

This analysis leads to the conclusion that the regional and national energy planning should work to encourage the adoption of special technologies for the rational use of fossil fuels in air conditioning systems, in particular by fostering "retrofit" interventions in the medium and large size building complexes. If the Thermal engineering that concerns air conditioning building legislation is committed above all to the "Reduction of heat loss” through the external shell of the building and through the pipes, it is also due to the fact that the " Calorimetric conception of Heat " is still predominant, whereas the "thermodynamic nature of Heat" which is a little neglected must be the basis for the theory and practice to achieve "the Rational Use of Energy" (RUE). As much as the above is of primary importance the technological solutions to be proposed are based on a modern and rigorous thermodynamic analysis.

3. Review of the thermodynamic fundamentals for the Rational Use of Energy

We remember that by definition it is said that a material system has an Energy 'E' if it has the potential to complete a work L = E. The 1st law of thermodynamics for a closed thermodynamic system permits the following: $Q_{1,2} - L_{1,2} = \Delta U_{1,2}$ where $Q_{1,2}$ is a quantity of heat exchanged in a process that brings the system from an initial state 1 to a final state 2; if the process occurs at internal energy U constant, becomes $Q_{1,2} = L_{1,2}$. This result signifies that the Heat "Q" is not only that entity defined and measured in Calorimetry and flows from one body to another according to Fourier's law of conduction, but "also contains Energy", it expresses the amount of thermal Energy. However for the 2nd Law of Thermodynamics to extract from heat $Q_{1,2}$ the work $L_{1,2}$ in a "practically convenient" way it is necessary to do it with a "cyclical" machine i.e. bithermical. Therefore, the effective potential that the Heat Q has to be converted into work is expressed by the Work obtainable by the ideal Bithermal machine, the machine of Carnot, which function in contact with the Reservoir of Thermal Energy (RTE) at temperature T top, but also in contact with a RTE to minimum temperature T_0. This ideal Work is called "Energy available for Work" or simply "Exergy" and is expressed by:

$$Ex(T) = Q\left(1 - \frac{T_0}{T}\right) \qquad (1)$$

which constitutes the definition of Exergy of heat Q available at the temperature T, being fixed by convention T_0 equal to the planetary temperature of 288 K [3]. Rarely is available in nature Heat at temperatures T high enough and therefore having a high value of Exergy. This definition of Exergy also applies to the heat Q extracted at top temperature T from the combustion processes that take place in boilers and steam generators. In addition when the process is irreversible, the 2nd Law of Thermodynamics for a general isolated system (consisting of several subsystems), which has its own entropy $S_{c,isol}$, imposes the inequality:

$$\Delta S_{C-isol} \geq 0 \qquad (2)$$

Finally, it is important to remember that when an irreversible process produces an increase in the Entropy of the isolated general system, equal to eq.(2), these irreversibility causes the "loss of a quantity of Exergy" (Energy unavailable for work) [3] equal to:

$$Ex_{loss} = T_0 \Delta S_{C-isol} \qquad (3)$$

Using the above equations and the equations of Flow processes, thermodynamic calculations can be made of the *flows of Energy and Exergy* associated with all the processes that occur in industrial and in civil plants such as air conditioning systems. Therefore it is useful to analyze the suitable processes for reducing the loss of Exergy (eq.(3)) "for the optimal choice of the air conditioning plants ".

a) *Steam Generator*. From the exergetic analysis for a steam generator powered by fossil fuel it is apparent that the energy efficiency is very high, equal to 0.93, while the exergetic efficiency is much lower, equal to 0.47. The Exergy of the Heat "Q" extractable from the flame at the temperature $T = T_f$ is calculable by Eq. (1); but because of the irreversibility, in particular the thermal irreversibility due to the fall of temperature ΔT from the flame to the steam, the value of the lost Exergy Exp is calculable with Eq. (3) is significant; however, the Exergy of the water vapor product is even higher because its thermodynamic state has temperature T_u = (550°C +273.15) K and 200 bar, so it can be sent to a turbo alternator group to produce electric Exergy; this can be used to drive the heat pump electric compressor. It is noted that the heat discharged to the condenser of the thermoelectric plant has a temperature lower than 40°C, which makes heat recovery for an air conditioning system inefficient.

b) *Diesel engines*. While the steam generator plants are designed to exploit the Exergy of Heat at medium high temperature and discharge the heat to the condenser at a temperature that is too low, internal combustion motors, such as diesel engines, are suitable to take advantage of the Exergy of the combustion process at high temperature, calculable by the eq. (1), and discharging the combustion gases still at average high temperatures (about 500°C) with a usable Exergy, through the heat recuperator, for important processes. The generators and Cogenerator systems with a gas turbine have similar characteristics to the diesel engine with respect to the flow of Exergy.

c) *Conventional boiler*. Consider the same processes referred to in a) in a conventional boiler which produces hot water to t_u = 80°C. The boiler can produce a useful heat Q_u with high energy efficiency up to 0.95; the Exergy of Heat Q_u extractable at the temperature T_f of the flame (eq.1) is equal to the case of the steam generator observed in a); but the thermal irreversibility due to the great temperature drop ΔT from the flame to the water causes a much higher Exergy loss Exp calculable by the eq. (3), therefore the Exergy remaining in the hot water is very little; it follows that the exergetic efficiency of the boiler is a few units of percent; therefore such a boiler dissipates the Exergy of flame given by Eq. (1) because it is "a producer of Entropy" according to eq. (2).

d) *Heat pump.* Let us now examine the operating principle of Heat pump with the Exergy method. The Bithermal reversible heat pump can be schematized as a reverse cycle Carnot engine; at the start it transfers the Exergy provided (such as work) on a greater number of units of Heat Q_0 low Exergy, but with exergetic efficiency equal to one; because of the mechanical and thermal irreversibility the Heat pump has a real exergetic efficiency of the order of 0.5, therefore, the real energy performance can be between 3 and 4.

e) *Comparison of the Heat pump with the boiler*. If the Exergy that the boiler dissipates was in part converted into electrical work, as in a thermal power plant or in a Diesel engine, this work could power an heat pump unit; if this has energetic efficiency equal to 3 it could provide to the user a quantity of heat Q_u greater than that which the boiler would directly provide equal to the fuel used (and equal to specific low Exergy in output). If the electrical system had a territorial thermoelectric average energy efficiency of 0.33 with the electricity powering the heat pump at efficiency 3, the energy chain would achieve an overall efficiency of 1.0 (100%). Therefore with the "electric generator / Heat Pump building air conditioner" system, a significant primary energy saving and reduction in CO_2 emissions is not achieved, compared to an air conditioning system based on high efficiency boilers (0.95). *Characteristics of the "Diesel electric group / Cogeneration*". A medium power cogeneration diesel engine for continuous operation in a fixed installation that drives an electric generator can have a mechanical output on a shaft equal to 0.40; overall electrical efficiency of 0.38; Thermal efficiency of the recovery of heat from the engine and the exhaust gas equal to 0.39, The Heat still possesses sufficient Exergy. The Cogeneration Generator has a total energetic efficiency of 0.38 + 0.39 = 0.77 which seems small compared to the boiler of up to 0.95; but the generator has high exergetic efficiency; It has produced electric Exergy and can power the heat pump for the air conditioning system; with heat recovery from the exhaust gas which can also feed the thermal consumption in buildings and power the absorption refrigeration machines; while the boiler which supplies water at 80°C has an exergetic efficiency of almost zero, this is the fundamental difference.

4. Description of the existing fossil fuel plants at the University Campus

As stated in the planimetry of Figure 1, the proposed project for the University building complex consists of the following blocks: a) Lot 1 (buildings in red) consists of Asse, Spina, Spinetta and Stabulario unit for a total gross heated volume of approximately 90,300 m^3; b) Lot 2 (buildings in blue) consists of Asse and “Spina” for a total gross heated volume of about 87,400 m^3; c) Lot 3 (green buildings) comprised of only the “Spina” for a total gross heated volume of about 47 060 m^3. The handling units are arranged to perform a complete air-conditioning function. Winter heating of the complex takes place via a central facility with boilers, originally on heating oil, then converted to diesel fuel, which heat the heat transfer fluid (water-based) that is distributed to the terminals of heating / cooling, such as fan coil units and Air Handling. The hot water production takes place in the thermal power plant, located in a central area with respect to the building complex, consisting of three boilers including two major units of 4.3 MWt each and a smaller unit of 700 kWt mainly dedicated to the Stabulario building lot. The distribution of the heat transfer fluid to the various Lots occurs through piping networks, which run inside large section canals under the buildings, which feed thermal substations n° 4. At present, the refrigeration unit is missing; but the air conditioning terminals for these lots can be modified to be powered by cooled water. The total power of refrigeration required by existing utilities, which comprise the fan coils installed in the environments and Conditioning Unit mounted on the terraces, amounted to 1,487,560 kcal/h for buildings of Lot 1 and equal to 1,263,228 kcal/h for the Lot 2; the total cooling demand is therefore equal to 3,199 kW. Fuel consumption for heating: in the years when the volumes defined above have been fully served, the average annual consumption of diesel oil amounted to 424,000 litres/year.

5. Preliminary Project of a new air conditioning system in Cogeneration with Heat pumps

The results of the thermodynamic analysis carried out in the previous chapter direct the decision to propose a "Cogeneration System with Heat Pump and absorption chiller" to substantially improve the energy efficiency and environmental compatibility of an air conditioning system in the service of the existing building complex in the University of Cagliari campus situated in Monserrato. The new facility consists of a new Thermal power plant with Cogeneration; it is intended to equip the buildings of Lot 1 and Lot 2 with an air conditioning system that meets the needs in different seasons using the cooling and the heating function.

5.1. Refrigeration function and air conditioning in summer.

The project proposal includes a "*Refrigeration unit-type cogeneration centralized*" which has to feed the circuits of the existing fan coils and the existing conditioner circuits (CDZ) The capacity of the existing air conditioning terminals is 3200 kW. Based on this power rating required by existing buildings it was decided to size the refrigeration system to heat pumps and cogeneration as follows:

1)Two diesel engine cogeneration Groups of 730 kWe each, for continuous operation, connected in parallel with the regional ENEL (National Electricity) network through a special electrical parallel panel with the following main features: 'Diesel cycle oil Engine'. Mechanical power supplied to the motor shaft according to ISO 3O46 / DIN 6271 (ICFN): 768 kW; Thermal power introduced into the first engine 1895 kW, corresponding to 160 kg / h of diesel oil. Net electrical power output from the alternator to power factor = 1: 730 kW. Heating power recoverable or to be disposed of by the water side and engine oil 314 kW, side exhaust engine 430 kW; Total heat capacity 744 kWt. The Cogenerator has the following returns: Electrical efficiency 38.5%, 39.2% thermal efficiency; Overall efficiency of 77.7%. Exit exhaust gas temperature from the engine 485°C. The engine is equipped with a traditional electric radiator, commanded by the control circuit for emergency operation.

2) A circuit of the heat recovery of each diesel engine produces water at 95°C for post summer reheating, and for the sanitary water; the recovery of heat from the exhaust gas feeds the absorption refrigeration machines with water at 132°C. 3)Four refrigeration/heat pumps total recovery type, that are capable of providing continuity with hot and cold water simultaneously, the cooling capacity equal to 4x1000 kW, powered by electricity produced by the electric generator cogeneration Groups in 1). 4)The absorption refrigeration machines operate with the absorbent-absorbed pair of lithium bromide -water. They are supplied with water at 132°C by the exhaust gases of the generators and have a cooling efficiency of approximately 1.07. Two refrigeration machine of unit power yield 400 kWt are planned. The refrigerating machine has the condenser chilled by cooling tower water that enters and exits at 30°C to 35°C; and the evaporator which delivers water at 7°C with Δt of 5°C. 6) The evaporative water cooling towers for cooling water of the external circuit of the condenser of the refrigerating machine are of the helical fan type with high efficiency; which provide the refrigerating machines with water at a temperature of 35/30°C. 7) The Diesel oil deposit is located in the central heating and refrigeration unit containing the sets; which consists of four steel standard type underground tanks of 10 m^3 each.

5.2. Winter heating and sanitary water

The cogeneration system with heat pumps described in parag.5.1 is connected in parallel to the existing circuit of boilers, in the main existing thermal power plant site, which is always useful in case of failure of the heat pumps or for scheduled maintenance; but the main function of heating carried out by the new Central Cogeneration is a replacement of the function of the existing heating oil and diesel boilers. This cogeneration system with heat pumps can provide a thermal heating total of the following contributions: 1) Each diesel engine can deliver a thermal power to the order of 744 kWth, therefore in total kWth 2x744=1488 kW_{th} through the recovery circuit of the refrigeration heat of the two motors, in the winter the absorbers are stationary. The 4 Heat Pumps have the following characteristics; Winter operation: 1) the tube bundle heat exchanger which is connected to the main hydraulic circuit will function as the condenser (the finned coil will function as an evaporator). The eventual freon/water exchanger dedicated to the partial heat recovery (desuperheater) will allow the production of hot water in a second hydraulic circuit dedicated to the production of hot water for sanitary use or otherwise. 2) The total rated thermal input is equal to 4,200 + 1,488 = 5,688 kW which is sent through new pipes that connect the new Cogeneration station with the existing thermal station and the existing substation Lot 2 (see Fig.1).

6. System performance and benefits for the economics and the Environment

Based on the exergetic analysis presented, we verify the energy performance of the conditioning Plant powered by an Air Conditioning power plant of the type proposed in the functional diagram of Fig- 1; high values of overall energy efficiency "r" in the winter heating can be achieved, which can be verified with a simple calculation.

Assuming that the average seasonal temperature in Cagliari and in coastal areas of southern Italy is about 12°C, that the plant has a daytime operation, which in the local climate the average seasonal power is about equal to ½ of the nominal capacity, we can estimate the generating efficiency values shown in the parag.5.1 pt.1) as certified by the manufacturer, for heat pumps we estimate an energy efficiency (COP) equal to 3, you can write:

$r = Q_u / E_{c,m} = (Q_{HP} + Q_R) / E_{c.m} = E_{c.m} [(0.38x3) + 0.39] / E_{c.m} = 1.53$; being $Q_u = Q_{HP} + Q_R$ Heat supplied to the users of the buildings, indicating $E_{c,m}$ primary Energy fuel going into the engine; $Q_{HP} = (0.38E_{c.m}\ x3)$ indicates the output heat from the heat pump, $Q_R = 0.39xE_{c.m}$, indicates the output heat from the recuperator of the engine.

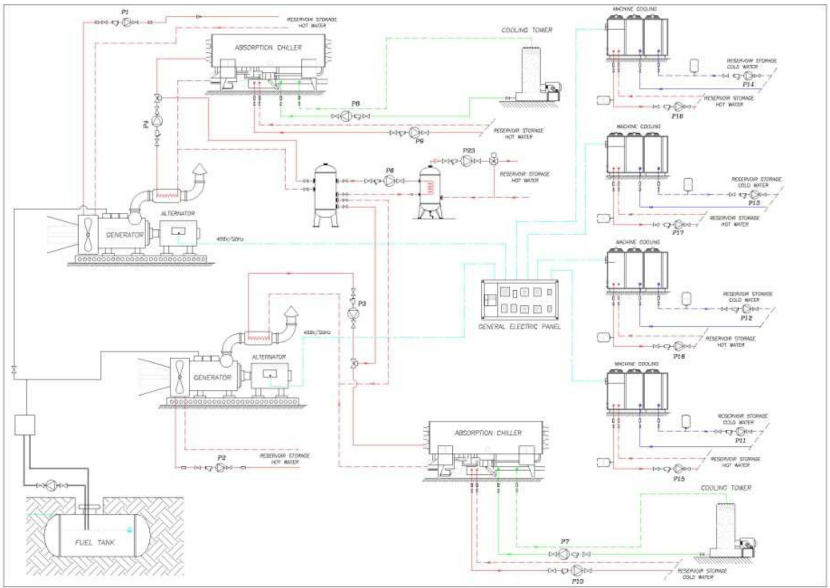

Fig. 1. Block diagram of the Cogeneration system with Heat pumps and absorption refrigeration machines

These results are achieved by applying good thermodynamics in air-conditioning plants that not only seek to use the energy of the Heat with high energy efficiency, but look for processes that use the Exergy Fuel and Heat to the best. With regards to its winter function, the efficiency of the diesel fuel heating plan boilers as an average seasonal value may be 0.85, while the energy efficiency of the Cogeneration power plant with heat pump is about 1.50; Therefore, the relationship between the consumption of fuel and the needs of the plant in Cogeneration boiler plants is 0.85 / 1.53 = 0.56; it follows that the mass of fuel required by the Cogenerator is equal to 0.56x (required mass from the boilers); the annual saved mass is 0.44x (required mass boilers). In the case of the system under consideration the mass of fuel in winter that can be saved is equal to 424,000x0.44=186560 litres of diesel. The emissions of CO_2 and other pollutants emitted from the boilers are reduced by about 40%. In summer operation not only saves on the cost of the electricity self produced but also because it uses the recovery of heat from the engine.

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